

Forecasting the Impact of Technology Infusion on Subsonic Transport Affordability

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Georgia Institute of Technology

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Forecasting the Impact of Technology Infusion on Subsonic Transport Affordability

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ABSTRACT

The design of complex systems, such as commercial aircraft, has drastically changed since the middle 1970's. Budgetary and airline requirements have forced many aerospace companies to reduce the amount of time and monetary investments in future revolutionary concepts and design methods. The current NASA administration has noticed this shift in aviation focus and responded with the "Three Pillars for Success" program. This program is a roadmap for the development of research, innovative ideas, and technology implementation goals for the next 20 years. As a response to this program, the Aerospace Systems Design Laboratory at Georgia Tech is developing methods whereby forecasting techniques will aid in the proper assessment of future vehicle concepts. This method is called Technology Impact Forecasting (TIF). This method is applied to a medium-range, intra-continental, commercial transport concept. The method identifies system level metric values, including performance and economics, for present day technology levels and projects this vehicle into the year 2020. Four technologies are applied to the vehicle including composite wing and fuselage structures, circulation control, hybrid laminar flow control, and advanced flight control systems. The projection of this vehicle into 2020 could not satisfy the target percent reduction with respect to the affordability goals set forth in the "Three Pillars for Success" program. However, the power/advantage of the TIF method is clearly seen in this instance. In lieu of the blunt statement of failure, which provides no understanding or insight of the contributing factors or the method of resolution, a probabilistic environment is created for the decision maker/designer to play "what if" games. The ability is now present to assess the effect of relaxing target values, infusion of numerous technologies, and exploration of geometric design space decisions on the affordability of a future vehicle concept.

INTRODUCTION

Since the middle 1970's, global and national budgetary requirements and restrictions have drastically impacted the design of complex systems, specifically commercial aircraft. Government and industry are at a point where every dollar spent on a project must be justified as relevant to the company profits or national/societal investments. In fact, the design of any new complex system is driven by the bottom line system cost effectiveness rather than the traditional maximum performance. The focus on the bottom line has forced many aerospace companies to merge, downsize, and dismiss new, innovative,

and revolutionary designs due to economic risks and potential loss of profitability. As a consequence, new concepts, and technologies must buy their way onto an aircraft. Furthermore, the desires/needs of the traveling public are becoming increasingly more important. The traveling public wants the time savings associated with air travel but also desires comfort, safety, and affordability. These shifting currents of aviation have evoked a response from the current NASA administration:

"To preserve our Nation's economic health and the welfare of the traveling public, NASA must provide high-risk technology advances for safer, cleaner, quieter, and more affordable air travel." [1]

-- Daniel S. Goldin, NASA Administrator

This quote is one pillar of NASA's "Three Pillars for Success" program. This program is a roadmap to focus U.S. aerospace endeavors for the next 20 years in accordance with the changing environment of future aviation. Another pillar is revolutionary technology leaps. "An enabling technology goal of this pillar is to provide next-generation design tools (and methods)...to increase design confidence, and cut the development cycle time for aircraft in half [1]". It is a challenge for government and academia researchers to respond to these long-term goals and develop means for which implementation by industry can occur. In particular, long term goals have been set for percent reductions in affordability, safety, etc. for next-generation vehicle concepts. The question now at hand is how to determine or project if these goals can be achieved. In other words, a rapid forecasting method or technique is needed which can quantify next-generation concept performance and economic aspects and compare these results to the stated goals. The method(s) must be efficient to reduce design cycle time while capturing the impact of design decisions on the affordability of a vehicle system; since what is technically optimal may not be the most economically viable or most affordable. Herein, the authors present a method which addresses the issues of the design of a future complex system with focus on affordability. This method accounts for multi-attribute, -objective, and -constraint problems in the presence of operational and economic uncertainty, requirement ambiguity, and conflicting objectives. Furthermore, the process allows for the infusion and subsequent affordability assessment of new technologies while considering technological and economic risk. The process utilizes various techniques developed in other fields including Response Surface Methodology [2, 3, 4], Robust Design Simulation [4, 5, 6], and Fast Probability Integration [7].

APPROACH

The methodology developed by ASDL to forecast the performance and economics of future vehicle concepts is depicted in Figure 1. The methodology contains six steps for implementation. These steps are:

1. Define the problem
2. Determine system feasibility
3. Determine system economic viability
4. Evaluate probability of success
5. Infuse new technologies
6. Examine design solution and robustness

This methodology has been applied to a High Speed Civil Transport [8] and a high capacity, long range commercial transport [9]. The current investigation seeks to expand on these applications by considering the robust solutions for a family of vehicle concepts. The robustness of a design solution is an imperative goal for modern aircraft design theory. The design of any complex system is inherently uncertain rather than deterministic. This uncertainty arises from various contributing factors including analysis tool fidelity, manufacturing tolerances, daily fuel costs, etc. Hence, a robust design solution is one for which the design is capable of operating in a wide variety of environments with minimal variance in performance or costs.

The goal of this methodology is to provide a forecast environment for future vehicle concepts where technically feasible robust solutions can be identified with accuracy and speed and the economic aspects quantified. This methodology will aid the decision maker/designer to identify feasible and viable alternatives for research investments to meet future aviation demands. For this study, current technology levels are assumed to be for the year 1997 and projection of future feasibility and viability is for the year 2020. Also, all economic projections are in fiscal year 1997 dollars.

DEFINE THE PROBLEM (STEP 1)

The first step in any design method is to define the problem. Typically, the problem statement is driven by societal needs. Based on these needs, or customer requirements, a class

of vehicle concepts can be identified which may satisfy all imposed constraints and objectives. For example, commercial world air travel is expected to grow at a rate of 5.5% per year over the next decade [10], resulting in a 71% increase from current levels within a decade and increasing 192% in two decades. These projections have spawned interest in various vehicle concepts to respond to the predicted growth, including a long-range, high capacity commercial transport and a medium-range, intra-continental commercial transport. For this study, a medium-range, intra-continental commercial transport is the class of vehicles to be investigated.

Once the societal need is established, the customer requirements must be mapped into some engineering or mathematically quantifiable terminology. This terminology is in the form of system product and process parameters, referred to here as metrics. Metrics are figures of merit that characterize various disciplines involved in a system's development. The metrics for this study are economic and performance based and are listed in Table I, including the Direct Operating Costs per trip plus Interest (DOC+I) and the Total Airplane Related Operating Costs (TAROC). The two economic parameters, DOC+I and TAROC, have recently become important metrics for measuring commercial transport affordability. DOC+I constitutes approximately 55% of the passenger ticket price and includes: flight and cabin crew salaries, engine and airframe maintenance, fuel and APU costs, insurance, depreciation, interest, and landing fees. TAROC is the DOC+I plus ground handling; ground property, maintenance, and depreciation; and ground general and administrative costs, and constitutes an additional 10% of the passenger ticket price.

As stated previously, target values for these metrics are a percent reduction from present day levels, i.e., 1997 predictions. Therefore, a baseline configuration for 1997 was established for a 3,000 nm mission with the cruise segment at a maximum altitude of 35,000 ft at Mach 0.83. The baseline aircraft for this study was similar to a Boeing 737-800. The payload of the aircraft was assumed to be 150 passengers plus baggage, flight crew of two, four flight attendants, two wing-mounted engines, and a fuselage length and diameter of 117.8 ft and 12.58 ft, respectively. Basic vehicle parameters for the 1997

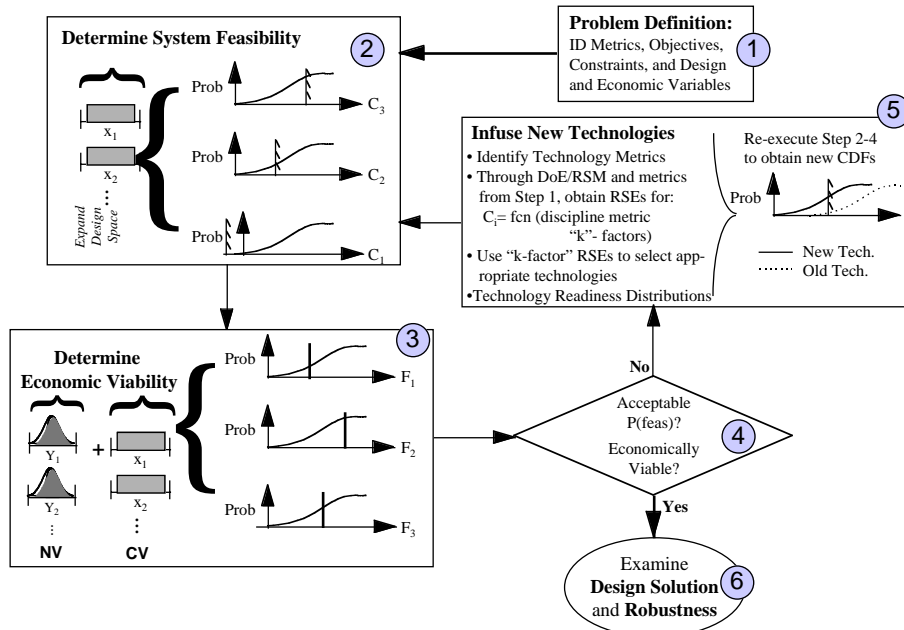


FIGURE 1: OVERALL METHODOLOGY FLOW

baseline are listed in Table II. Furthermore, to establish a datum point for viability, primary economic assumptions were established (Table III) which were used for the remainder of this study unless otherwise stated. A production learning curve (LC) was assumed for two lots.

All aircraft sizing and analysis tasks for this study utilized the Flight Optimization System, FLOPS, a multidisciplinary system of computer programs used for the conceptual and preliminary design and analysis of aircraft configurations [11]. This tool was developed by the NASA Langley Research Center. FLOPS was linked to the Aircraft Life Cycle Cost Analysis, ALCCA, program used for the prediction of all life-cycle costs associated with commercial aircraft. ALCCA was originally developed by NASA Ames and further enhanced by Aerospace Systems Design Laboratory (ASDL) [12].

Based on the geometric and propulsive parameters listed in Table II and the economic assumptions in Table III, baseline metric values were established through a sizing of the vehicle in FLOPS and subsequent economic analysis in ALCCA. As a result, quantitative values of the percent reduction in metrics were established. The projected metric target values for the year 2020 are listed in Table IV for the configuration shown in Figure 2.

These top level metrics can be further decomposed into product and process characteristics. Primary product characteristics include the physical design parameters which describe a system (i.e., wing area, thickness-to-chord ratios). In the conceptual design phase, these parameters are not yet determined and can vary within some specified range for a class or family of vehicle concepts. The product characteristics are the key design variables or parameters (with associated ranges) which define the design space of interest. These design variables are often referred to as “control” factors, or variables within the designer’s control. The control factors identified for this study are listed in Table V. It is this space which will be investigated for technical feasibility. Whereas, the process characteristics include manufacturing, economic, and operational parameters (i.e., production learning curves, passenger load factors, fuel cost), which are inherently uncertain and are often referred to as noise factors. From previous work performed at ASDL, the economic parameters of interest, which will most influence the stated metrics, are listed in Table VI [4, 5, 6, 9]

TABLE I: QUALITATIVE SYSTEM LEVEL METRICS

| Parameter | Target* | Constraint | Units |
|---|-----------------|-----------------|-------|
| <u>Weights and Performance</u> | | | |
| Approach Speed (V_{app}) | <i>minimize</i> | ≤ 130 | kts |
| Fuel Burn | -48% | <i>minimize</i> | lbs |
| Landing Field Length (Landing FL) | -21% | $\leq 7,000$ | ft |
| Operating Empty Weight (OEW) | -40% | <i>minimize</i> | lbs |
| Takeoff Field Length (TOFL) | -21% | $\leq 7,000$ | ft |
| Takeoff Gross Weight (TOGW) | -31% | <i>minimize</i> | lbs |
| <u>Economics</u> | | | |
| Direct Operating Costs + Interest (DOC+I) | -42% | <i>minimize</i> | ¢/ASM |
| Total Airline Related Operating Costs (TAROC) | -37% | <i>minimize</i> | ¢/ASM |

TABLE II: 1997 BASELINE PROPERTIES

| Parameter | Baseline 1997 | Unit |
|--------------------------|---------------|-----------------|
| <u>Wing</u> | | |
| Aspect Ratio | 9 | ~ |
| Auxilliary power unit | 1 | ~ |
| Flap ratio: Flap area/SW | 0.2569 | ~ |
| Planform Area (SW) | 1600 | ft ² |
| Quarter-chord Sweep | 30.5 | deg. |
| Root Thickness-to-chord | 13.5 | % |
| Taper Ratio | 0.25 | ~ |
| Tip Thickness-to-chord | 9 | % |
| <u>Engine</u> | | |
| SLS Thrust | 21974 | lbs |
| Bare weight | 3504.2 | lbs |
| Length | 9.83 | ft |
| Maximum diameter | 5.17 | ft |
| <u>Vertical Tail</u> | | |
| Area | 257.8 | ft ² |

TABLE III: ECONOMIC ASSUMPTIONS

| Parameter | Value | Parameter | Value |
|--------------------------|------------|--------------------------|-------------|
| Average Annual Inflation | 7.50% | Fiscal Year Dollars | 1997 |
| Airframe LC for 1st lot | 81.5% | Fixed Eq. LC for 1st lot | 82.0% |
| Airframe LC for 2nd lot | 85.0% | Fixed Eq. LC for 2nd lot | 85.0% |
| Assembly LC for 1st lot | 76.0% | Fuel Cost | \$0.71/gal |
| Assembly LC for 2nd lot | 79.0% | Load Factor | 65% |
| Avionics LC for 1st lot | 81.5% | Maintenance Labor Rate | \$19.50/hr |
| Avionics LC for 2nd lot | 85.0% | Production Quantity | 640 units |
| Downpayment | 0% | Airline ROI | 10% |
| Economic Life | 20 yrs | Manufacturer ROI | 12% |
| Economic Range | 2000 nm | Tooling Labor Rate | \$54.68/hr |
| Engineering Labor Rate | \$89.68/hr | Utilization | 3810 hrs/yr |

TABLE IV: QUANTITATIVE METRIC TARGETS

| Parameter | 1997 value | Target* | 2020 target | Units |
|--------------------------------|------------|-----------------|-------------|-------|
| <u>Weights and Performance</u> | | | | |
| V_{app} | 115.8 | <i>minimize</i> | ~ | kts |
| Fuel Burn | 44345 | -48% | 23059 | lbs |
| Landing FL | 4949 | -21% | 3908 | ft |
| OEW | 73864 | -40% | 44318 | lbs |
| TOFL | 5968 | -21% | 4715 | ft |
| TOGW | 149709 | -31% | 103300 | lbs |
| <u>Economics</u> | | | | |
| DOC+I | 5.41 | -42% | 3.14 | ¢/ASM |
| TAROC | 6.36 | -37% | 4.00 | ¢/ASM |



FIGURE 2: BASELINE AIRCRAFT

* Relative to ASDL 1997 Baseline values

TABLE V: DESIGN VARIABLES

| Parameter | Minimum (-1) | Maximum (+1) | Units |
|---|-----------------|-----------------|-----------------|
| Wing aspect ratio (AR) | 7.5 | 10.5 | ~ |
| Wing area (SW) | 1100 | 1700 | ft ² |
| Wing sweep (SWEEP) | 26 | 35 | deg. |
| Wing taper ratio | 0.21 | 0.29 | ~ |
| Wing root thickness-to-chord (t/c root) | 11 | 14 | % |
| Wing tip thickness-to-chord (t/c tip) | 8 | 10 | % |
| Thrust-to-weight ratio (T/W) | 0.28 | 0.32 | ~ |
| Wing flap ratio | 0.2 | 0.26 | % |
| HT Area | 250 | 350 | ft ² |
| VT Area | 0 | 260 | ft ² |
| Wing Height | 11 | 15 | ft |

TABLE VI: ECONOMIC VARIABLES

| Parameter | Minimum (-1) | Maximum (+1) | Units |
|-----------------------|-----------------|-----------------|--------|
| Economic Range | 1500 | 3000 | nm |
| Production Quantity | 500 | 800 | ~ |
| Passenger Load Factor | 55 | 85 | % |
| Fuel Cost | 0.65 | 0.9 | \$/gal |
| Airline ROI | 5 | 20 | % |
| Manufacturer ROI | 5 | 15 | % |
| Utilization | 3000 | 4500 | hrs/yr |
| Learning Curve* | -2.5 | +2.5 | % |
| Labor Rates* | -10 | +10 | % |

* Deviation from baseline values

DETERMINE SYSTEM FEASIBILITY (STEP 2)

To establish the concept system feasibility, the design space of a conventional configuration is initially investigated. This investigation was used to identify if the 1997 design space can meet the 2020 goals set forth in Table IV. If not, the investigation will serve as a benchmark to show how much improvement is needed for this vehicle concept in 2020.

There exists an infinite number of design variable combinations or settings which define the space of interest. There are three methods by which this space can be investigated for feasible solutions: 1) linkage of an actual simulation code with a Monte Carlo simulation; 2) creation of a Metamodel and linkage to a Monte Carlo model; and 3) Fast Probability Integration (FPI) [7, 13]. Each of the three methods results in a cumulative distribution function (CDF) for each metric as seen in Figure 1. Due to uncertainty in the design process, the results are probabilistic rather than deterministic, and the CDF provides the probability of achieving a given target value of a metric. The first method is the most accurate and most computationally intense since the analysis tool is executed directly. Typically, ten thousand random simulations of the analysis code must be executed for a good CDF. The second method uses a particular metamodel called a Response Surface Equation (RSE) to approximate the analysis tool and a Monte Carlo simulation is performed on this equation. This method has been applied for various investigations [4, 5, 6, 8] but has a limit in the number of variables for a second-order approximation. The third method (FPI) is used to approximate the CDF of the metrics directly using the analysis tool with fewer analysis tool executions. This technique is very efficient and accurate and has been applied in References [9, 13]. It is the designer's discretion as to which method is most suitable. For the purposes of this study, the third method for investigating the design space was utilized. A brief description of FPI is given below.

The FPI computer program [7], developed by researchers at the Southwest Research Institute for the NASA

Lewis Research Center, is a probability analysis code based on the determination of a Most Probable Point (MPP). The MPP analysis utilizes a response function $Z(\mathbf{X})$ that is a function of several random variable distributions. Each point in the design space spanned by the \mathbf{X}_i 's has a specific probability of occurrence according to their joint probability distribution function. Thus, each point in the design space corresponds to one specific response value $Z(\mathbf{X})$ which has a given probability of occurrence.

In cost analysis and other disciplines involving random variables, it is often desirable to find the probability of achieving response values below a critical value of interest, z_0 . This critical value can be used to form a Limit-State Function (LSF)

$$g(\mathbf{X}) = Z(\mathbf{X}) - z_0 \quad (1)$$

where values of $g(\mathbf{X}) \geq 0$ are undesirable. The MPP analysis calculates the cumulative probability of all points that yield $g(\mathbf{X}) \leq 0$ for the given z_0 (Figure 3). Since the LSF "cuts off" a section of the joint probability distribution, a point with maximal probability of occurrence can be identified on that LSF. This point is called the MPP. It is found most conveniently in a transformed space in which all random variables are normally distributed. Once the MPP for a given probability is identified, the process can be repeated for several z_0 values, mapping each probability over the normalized distribution space to get a CDF.

This study utilized the Advanced Mean Value analysis mode in FPI for all design space assessments. For a metric of interest, e.g., TOFL, a series of probabilities of achieving given metric values was calculated. FPI wrapped around FLOPS/ALCCA and controlled the variation of inputs in accordance with uniform probability distributions of the design variables listed in Table V and calculated the CDF based on the previously described method. This process was repeated until the CDF for all the specified system level performance metrics were established.

DETERMINE SYSTEM ECONOMIC VIABILITY (STEP 3)

The economic viability of the 1997 design and economic space was determined by executing FPI with uniform distributions for the design parameters (Table V) and normal distributions for the economic parameters (Table VI) where the mean value is the midpoint of the range stated. The CDFs to be approximated are DOC+I and TAROC. FPI generated CDFs for these economic metrics which are valid for the spaces under consideration. The viability assessment was performed in the same manner as the technical feasibility with the CDF targets.

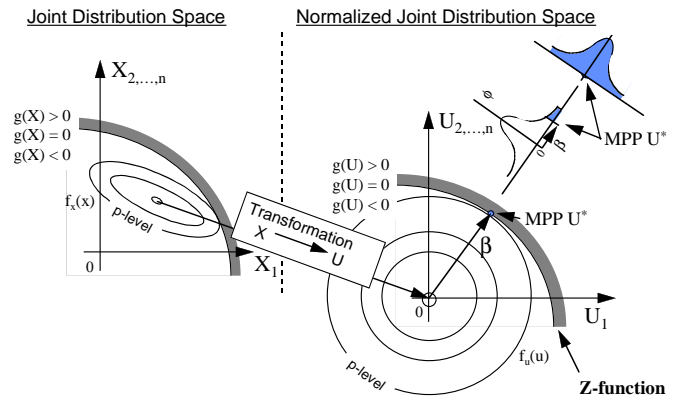


FIGURE 3: FPI CDF GENERATION

EVALUATE PROBABILITY OF SUCCESS (STEP 4)

The evaluation of the probability of success entails the concurrent examination of all performance and economic CDFs. For the feasibility study, all economic parameters were set to a most likely value. Since only Vapp, Landing FL, and TOFL were constrained, these three metrics were the only ones which could inhibit feasible designs for the 1997 concepts. The TOFL could only meet the imposed constraint of 7,000 ft with 71.4% of the designs considered. This result is shown in Figure 4. Also, Vapp and Landing FL could meet the constraints with a 80.6% and 100% probability, respectively. These results were based on the 1997 constraint, not the 2020 goals. But, if the 1997 design space is compared against the 2020 performance goals, which decrease the feasible design space significantly, one has to come to the conclusion that the 1997 baseline does not satisfy the targets set forth in NASA's "Three Pillars to Success" program.

As for the economic viability of the 1997 conventional design space, no specific constraints are imposed. Yet, the DOC+I and TAROC for the conventional space are of interest to determine if the projected 2020 goals can be achieved without the infusion of technologies or relaxation of the projected targets. As illustrated in Figure 5, a conventional design space cannot achieve the 2020 economic targets for TAROC. A similar result was obtained for the DOC+I.

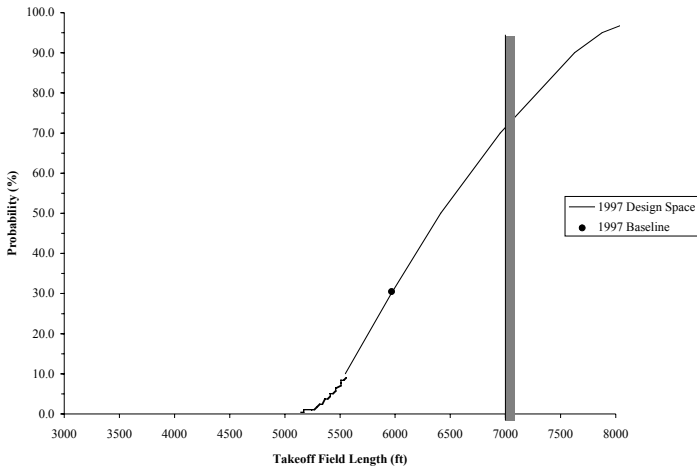


FIGURE 4: TECHNICAL FEASIBILITY ASSESSMENT (TOFL)

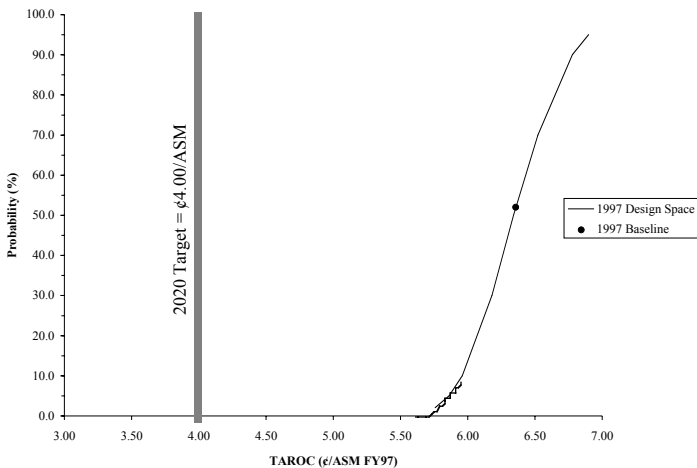


FIGURE 5: ECONOMIC VIABILITY ASSESSMENT (TAROC)

INFUSE NEW TECHNOLOGIES (STEP 5)

The evaluation of concept feasibility and viability is based on the value of the probability of a given metric to meet the specified target value on the CDF. For example, if a metric has an 80% chance of achieving the target, the decision-maker may decide that it is no longer a constraint and does not warrant further investigation. Yet, a low probability value (or small confidence) of achieving a solution that satisfies the constraints implies that a means of improvement must be identified. This includes, but is not limited to, the infusion of new technologies. The infusion of a technology is required when the manipulation of the variable ranges has been exhausted, optimization is ineffective, constraints are relaxed to an extremal limit, and the maximum performance attainable from a given level of technology is achieved. The maximum level of a given technology is essentially the natural limit of the benefit. This implies that the maturation variation with time remains constant. When this limit is reached, there is *no other alternative* but to infuse a new technology. As evident in Step 4, feasibility and viability for the specified 2020 targets could not be achieved with 1997 design standards and infusion of technologies was needed.

The impact of a technology can be qualitatively assessed through the use of technology metric "k" factors. These "k" factors modify technical metrics, such as specific fuel consumption, cruise drag, and/or component weights, that result from some analysis or sizing tool. The modification is essentially a change in the technical metric, either enhancement or degradation and simulates the discontinuity in benefits and/or penalties associated with the addition of a new technology. If a "k" factor for a given technological metric is shown to improve the system metrics relative to the constraints or goals, that technology impact can be identified as worthy of further investigation. An actual technology must be identified which can provide the "k" factor projections. Furthermore, the penalties to other systems must be determined and subsequently applied. This process is described in more detail in References [8] for an HSCT concept and [9] for a high capacity commercial transport. In essence, this technique is the forecasting of the impact of a technology, also known as Technology Impact Forecasting (TIF). To implement the TIF environment, technology metric "k" factors associated with possible future technologies were established. The range of applicability of the "k" factors must consider the benefits and penalties to various vehicle subsystems. Ten possible "k" factors were identified and are summarized in Table VII. A virtual manufacturing technology is simulated through the T1 "k" factor.

The baseline concept was optimized so as to minimize the metric values listed in Table I. Furthermore, the authors assumed that the propulsive technology available in 2020 should be smaller and more fuel efficient. These engines were subsequently added to the optimal geometric baseline. A parameter comparison of the 1997 baseline to the optimal geometric baseline with the assumed 2020 engines is listed in Table VIII. A performance comparison of these two configurations is listed in Table IX. The optimal geometric baseline is the projected 2020 baseline to which the technology "k" factors were applied.

The purpose of the TIF environment is to allow a designer to investigate whether the infusion of technologies will overcome any "show-stoppers" and shift the metric CDF closer to a target value. This procedure was implemented with a Design of Experiments (DoE) method on the projected 2020 baseline. A DoE was utilized to create a metamodel of the system level metrics. The metamodel, in the form of Response

Surface Equations (RSEs), was a quadratic approximation of the metrics that result from the analysis tools, FLOPS/ALCCA. The reader is referred to References [2,3,4,5,6] for more information on the DoE method and RSE generation. The RSEs for the metrics are a function of the “k” factor parameters listed in Table VII for the fixed projected 2020 geometry. FLOPS was executed based on the settings prescribed by the DoE, appropriate data was extracted, and the RSEs were formed with the aid of the statistical package JMP [14]. The impact that the “k” factors have on the metrics can be visualized through the prediction profile feature of JMP. The prediction profile, shown in Figure 6 for the feasibility and Figure 7 for the viability, is evaluated based on the magnitude and direction of the slope, where the “-1” and “1” values, shown above the “k” factors, are normalized values with respect to the ranges identified in Table VII. The larger the slope, the greater the influence of the given parameter on a system level metric. If a parameter, listed on the abscissa, does not contribute significantly to the response listed on the ordinate, the slope is approximately zero. The sign of the slope, either positive or negative, depicts the direction of influence of the parameter on the metrics. Furthermore, the limits of the metrics can be readily obtained, e.g., the TOGW varies between 98,629 and 138,520 lbs and was most influenced by a reduction in fuselage weight and reduced wing area as expected. As evident, the infusion of technology *can* create a feasible design (Figure 6) with some combination of the “k” factor settings. But, as shown in Figure 7, the TAROC goal of 4.0 ¢/ASM and DOC+I goal of 3.14 ¢/ASM cannot be achieved with the chosen “k” factor ranges. This result was for a fixed configuration and may change once the design space is again opened. Three other economic parameters are shown in Figure 7 and include acquisition price, RDT&E costs, and first unit cost (T1) and are in FY97 \$M. It should be noted that a 10% reduction in T1 can simulate a 7% reduction in RDT&E costs.

The question at hand is: “What are the “k” factor settings and associated technologies which create a feasible and viable solution?” The answer is achieved through selecting specific technologies available at the vehicle entry into service date. Four potential technologies were identified which could mature to the point of wide-spread application in 2020. These include composite structures for the wing and fuselage, Circulation Control (CC) for low speed flight lift augmentation, Hybrid Laminar Flow Control (HLFC) for cruise drag reductions, and advanced flight control systems which removes the need for a vertical tail. The next aspect of the TIF method is to establish confidence estimates for each technology metric which include primary benefits and secondary penalties or benefits. The impact that these proposed technologies have on the “k” factors is shown in Table X. The impact was treated as probabilistic since the estimates are based on the projected readiness of the technology in 2020. If one assumes that the impact of the technologies on a “k” factor is additive, a confidence estimate frequency distribution may be established as shown in the last column. It should be noted that the manufacturing costs associated with the composite wing and fuselage structures was assumed to be mature to the point of equivalency of aluminum manufacturing costs today. Next, the impact that the specific mix of technologies had on the fixed vehicle was quantified. Since the simulated technologies are uncertain, the impact was assessed via a Monte Carlo simulation. The simulation was performed with the aid of the software package Crystal Ball [15] on the metric RSEs previously obtained. Based on the assigned confidence distributions in Table X, CDFs for each metric were obtained.

TABLE VII: TECHNOLOGY METRIC “k” FACTORS

| Parameter | Minimum (-1) | Maximum (+1) |
|---|-------------------|---------------------|
| Fuel Flow (k_Fuel flow) * | 82% | 105% |
| Cruise Total Drag (k_Drag) * | 85% | 100% |
| Wing Weight (k_Wing wt) * | 70% | 100% |
| Fuselage Weight (k_Fuse wt) * | 52% | 100% |
| Allowable Takeoff $C_{L_{max}}$ ($C_{L_{max}}$ TO) * | 90% | 150% |
| Allowable Landing $C_{L_{max}}$ ($C_{L_{max}}$ LD) * | 90% | 150% |
| Utilization (k_U) | 3000 hrs/yr | 4500 hrs/yr |
| RDT&E Costs (k_RDT&E) * | 90% | 110% |
| First Unit Costs (k_T1) ** | +10 % | -10 % |
| Vertical Tail Area (k_VT) | 0 ft ² | 260 ft ² |

* 100% corresponds to 1997 standards

** 0% corresponds to 1997 standards

TABLE VIII: PARAMETER COMPARISON OF PROJECTED 2020

| Parameter | Baseline 1997 | Projected 2020 | Unit |
|--------------------------|---------------|----------------|-----------------|
| <u>Wing</u> | | | |
| Aspect Ratio (AR) | 9 | 8.25 | ~ |
| Flap ratio: Flap area/SW | 0.2569 | 0.2082 | ~ |
| No. of flight crew | 2 | 1 | ~ |
| Planform Area (SW) | 1600 | 1400 | ft ² |
| Quarter-chord Sweep | 30.5 | 26 | deg. |
| Root Thickness-to-chord | 13.5 | 11.4 | % |
| Taper Ratio | 0.25 | 0.2132 | ~ |
| Tip Thickness-to-chord | 9 | 8.23 | % |
| <u>Engine</u> | | | |
| SLS Thrust | 21974 | 17556 | lbs |
| Bare weight | 3504.2 | 2393.4 | lbs |
| Length | 9.83 | 8.348 | ft |
| Maximum diameter | 5.17 | 4.296 | ft |

TABLE IX: PERFORMANCE COMPARISON OF PROJECTED 2020

| Parameter | Baseline 1997 | Projected 2020 | Unit |
|-------------------------|---------------|----------------|---------------------|
| <u>Weights</u> | | | |
| Fuel Weight | 44345 | 30733 | lbs |
| OEOW | 73864 | 67279 | lbs |
| TOGW | 149709 | 129513 | lbs |
| <u>Performance</u> | | | |
| V_{app} | 115.8 | 115.1 | kts |
| $C_{L_{max}}$ Landing | 2.468 | 2.468 | ~ |
| $C_{L_{max}}$ Takeoff | 2.102 | 2.102 | ~ |
| L/D at the top of climb | 17.137 | 16.901 | ~ |
| Landing FL | 4949 | 4697 | ft |
| SFC at top of climb | 0.6913 | 0.49514 | /hr |
| TOFL | 5968 | 3106 | ft |
| T/W | 0.29 | 0.29 | ~ |
| Wing Loading | 93.6 | 92.5 | lbs/ft ² |

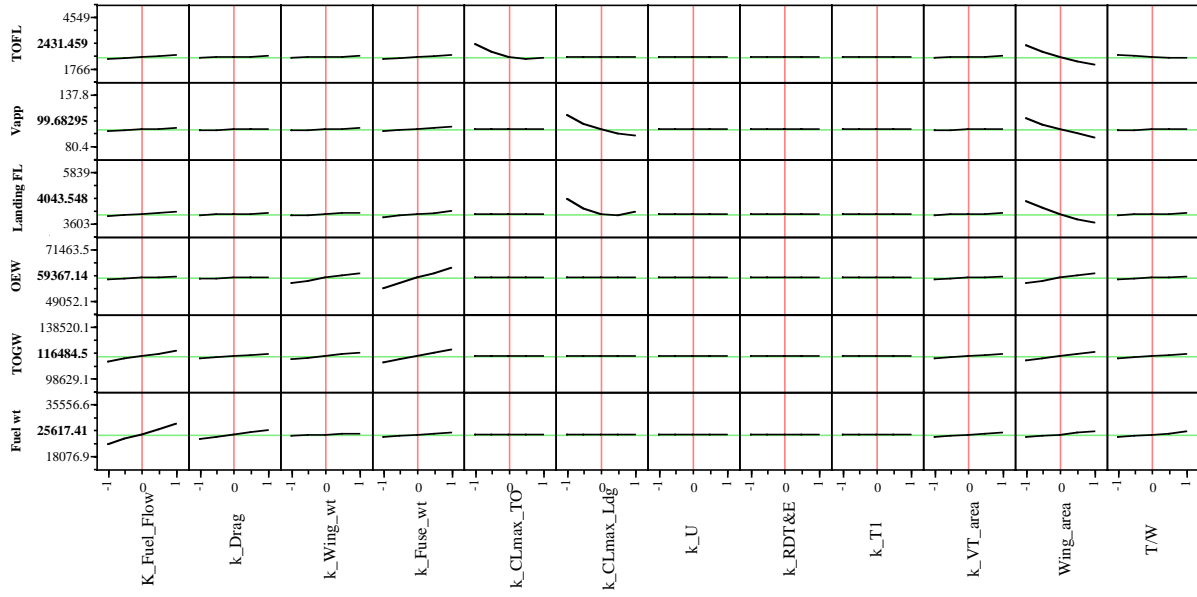


FIGURE 6: FEASIBILITY TIF ENVIRONMENT

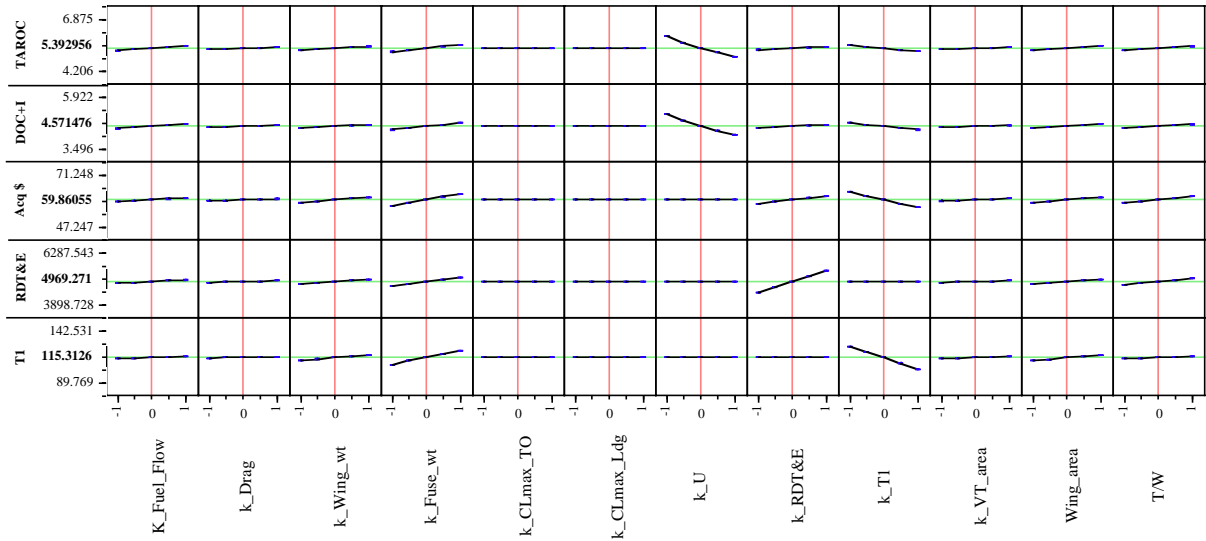


FIGURE 7: VIABILITY TIF ENVIRONMENT

The simulated impact of the specific technologies on the TAROC and DOC+I on the projected 2020 baseline are shown in Figure 8 and Figure 9, respectively. As evident, the mean of the CDF shifted closer to the target for each economic metric. The variance of the TAROC, or any other metric, is immediately visualized by the slope of the CDF. The steeper the slope, the smaller the variance. The solid line CDF represents the original 1997 design space. Even though neither of the economic metrics of the design space considered meets the 2020 goal, the difference between the goal and the specific technologies vehicle CDF is reduced. In fact, all eight metrics for the original 1997 design space could not meet the imposed goals for any designs considered. Yet, for the projected 2020 baseline with specific technologies, four of the eight metric goals (Table IV) could be achieved with some level of confidence: Vapp (100%), fuel burn (16.1%), Landing FL (62.5%), and TOFL (100%).

The OEW and TOGW shifted closer to the 2020 target just as TAROC and DOC+I. The mean values for OEW and TOGW were respectively only 15,291 lbs and 13,670 lbs from the 2020 goals. The decision maker/designer has at least three options at this point to create a feasible and viable configuration: one, relax the imposed metric goals and shift the target towards the metric distributions; two, be more aggressive with the assumed technology benefits to shift the CDF closer towards the target; or three, reinvestigate the design space with the four specified technologies and shift the distribution towards the 2020 targets. The latter option was considered for this study.

TABLE X: SPECIFIC TECHNOLOGY CONFIDENCE ESTIMATES

| Parameter | Tech #1 Composite Structures | Tech #2 CC | Tech #3 HLFC | Tech #4 Advanced Flight Controls | Confidence Estimate Frequency Distribution |
|--|------------------------------------|---------------|-----------------|--|--|
| $\Delta k_{\text{Fuel burn}}$ | - | - | - | -1% | |
| Δk_{Drag} | - | - | -10% | -2% | |
| $\Delta k_{\text{Wing wt}}$ | -20% | +2% | +3% | -1% | |
| $\Delta k_{\text{Fuse wt}}$ | -25% | - | - | - | |
| $\Delta C_{L_{\text{max}}} \text{ TO}$ | - | +40% | - | - | |
| $\Delta C_{L_{\text{max}}} \text{ LD}$ | - | +40% | - | - | |
| Δk_U | -2% | -2% | -2% | - | |
| $\Delta k_{\text{RDT\&E}}$ | +3% | +3% | +3% | +1% | |
| Δk_{Tl} | +3% | +3% | +3% | - | |
| Δk_{VT} | - | - | - | No VT | No VT |

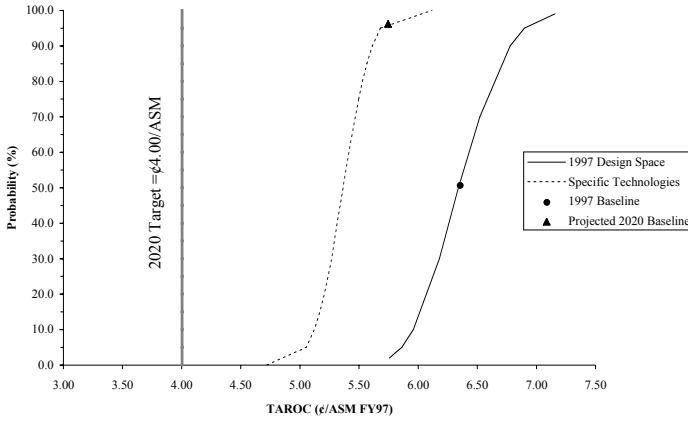


FIGURE 8: SHIFT OF TAROC VIABILITY CDF

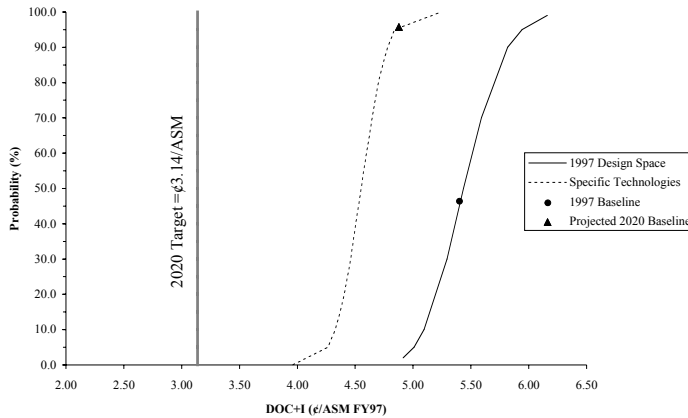


FIGURE 9: SHIFT OF DOC+I VIABILITY CDF

EXAMINE DESIGN SOLUTION; ROBUSTNESS (STEP 6)

Now, the question is posed: “Can varying the geometric properties shift the CDF even further to obtain the stated goals?” The answer to this question is achieved through the application of robust design techniques currently under development at ASDL.

Up to this point, the simulated technologies were applied to a *fixed* geometry. This fact was necessitated for two reasons. One, the isolated impact of technologies was desired to determine if feasibility and viability could be achieved. Second, the technology “k” factors are directly correlated to the geometric parameters of the vehicle concept. This correlation between “simulated” technologies and geometric settings can be overcome with two approaches. First, a statistical correlation matrix of the “k” factors to the geometry can be established. This approach is currently under investigation by the authors. The second approach, which was used for the current investigation, is to combine the DoE and FPI techniques. This approach intrinsically captures the correlation between design variables and technology metrics since the “k” factors modify only converged vehicle disciplinary metrics. In essence, the calculated disciplinary metrics are affected by the “simulated” technologies through a shift in the mean value, not the variance.

To implement this approach, the pertinent design variables from Table V were identified from a screening test in JMP. These parameters were aspect ratio, wing area, thrust-to-weight ratio, taper ratio, wing sweep, and thickness-to-chord ratios at the wing root and tip. All other geometric parameters remained at the projected 2020 baseline values. Next, a seven variable face-centered Central Composite DoE was set up in JMP. *For each simulation in the DoE table*, FPI was executed with normal distributions for the economic parameters in Table VI and for the “k” factors in Table X. This method is similar to the approach taken in Reference [4]. Now, the response of interest is *not* the deterministic metric value, but the CDF probability values of achieving that metric. For example, in lieu of one RSE representing the TAROC, nine RSEs were generated for the TAROC CDF probability values ranging from 2% to 99%. Hence, the RSE for the value of TAROC associated with a 50% probability is now a function of the economic variables and “simulated” technologies for a chosen geometry. This approach has removed the correlation between geometric variables and the technology factors. This approach was needed to open the design space to determine if the probability of a feasible and viable solution existed.

Five of the original eight system level metrics were identified as important for the design space investigation. These metrics were chosen due to low or nonexistent probability of success values obtained in Step 5 and include TAROC (0%), DOC+I (0%), Fuel weight (16.1%), OEW (0%), and TOGW (0%). The TOFL, Landing FL, and Vapp were not considered since the probability of meeting the 2020 targets with the assumed technologies was high as shown in Step 5. The reader is referred to References [8, 16, 17] for more detailed information on robust design methods.

As stated previously, a combined DoE/FPI approach was utilized to investigate the design space subject to economic and technological uncertainty. The data generated from this approach was supplied to JMP for the five metrics, and the RSEs for the CDF probability values were established. The RSEs associated with the 50% CDF probability are shown as a prediction profile in Figure 10. These trends were consistent for all other CDF probability levels. It is the decision makers/designers discretion as to which probability level to assume to identify if a geometry exists which will shift the

metric CDFs closest to the 2020 goals. For this study, a 50% level was assumed. The geometric settings which achieve this goal were an aspect ratio of 7.5, wing area of 1,100 ft², thrust-to-weight ratio of 0.28, taper ratio of 0.21, wing sweep of 35°, and a wing root and tip thickness-to-chord ratios of 14% and 8%, respectively. The resulting TAROC CDF for this new geometry is shown in Figure 11. As evident, the CDF *does* shift closer to the 2020 TAROC target, but still cannot create an economically viable solution. This result was also true for the DOC+I, TOGW, and OEW. Yet, with the new geometric settings, the fuel weight goal could be achieved with a 60% probability. For a probability of success of 50%, the following metric values were achieved, with the new geometric settings stated above: TAROC of \$5.13/ASM, DOC+I of \$4.365/ASM, TOGW of 108,322 lbs, OEW of 50,005 lbs, and Fuel weight of 22,762 lbs.

In spite of the fact that a feasible and viable space does not exist, there are three alternatives; one, relax the 2020 goals and shift the target towards the distribution; two, be more aggressive with the benefits associated with the specific technologies chosen or select alternative technologies which provide more benefits; or third, open the design variable ranges further and reinvestigate the space. Yet, for the targets and configuration under investigation for this study, feasibility and viability cannot be achieved.

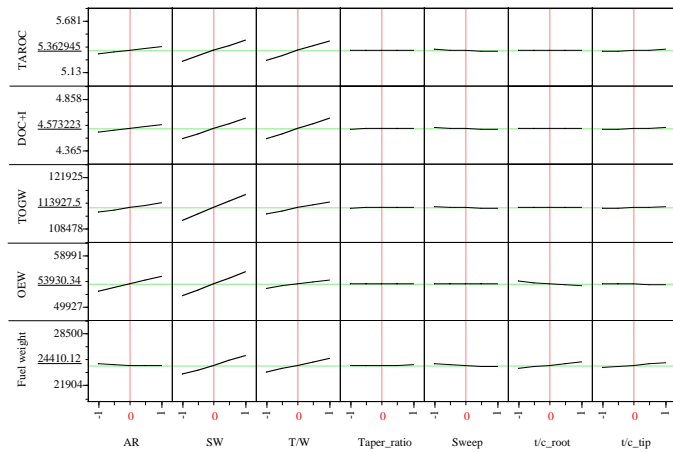


FIGURE 10: 50% PROBABILITY VALUE OF THE DESIGN SPACE

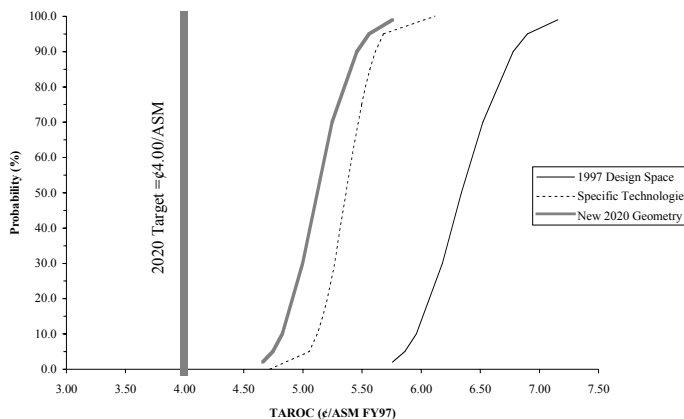


FIGURE 11: FURTHER SHIFT OF TAROC VIABILITY

CONCLUSIONS

This paper described a methodology under development at the Aerospace Systems Design Laboratory which aids the decision maker/designer in projecting performance and economic metrics for future vehicle concepts. This method allowed for the identification of various means by which future performance and economic goals may be achieved. A proof of concept investigation was performed on a medium-range intra-continental commercial transport. A design space investigation was implemented to establish present day metric values. Subsequently, 2020 targets were established based on NASA's "Three Pillars for Success" program target reductions. A present day configuration was projected to the year 2020 with the addition of advanced propulsive concepts and a feasibility and viability investigation performed. The projected 2020 baseline was shown to not be feasible or viable with respect to the following system level goals: total airplane related costs, direct operating cost plus interest, takeoff gross weight, and operating empty weight. Through the infusion of four technologies, the cumulative distribution functions of a given geometry, subject to economic and technological uncertainty, could be shifted closer to the 2020 goals. Even though the goals could not be achieved, three means of improvement were identified and include: one, relax the 2020 goals and shift the target towards the distribution; two, be more aggressive with the benefits associated with the specific technologies chosen or select alternative technologies which provide more benefits; or third, open the design variable ranges further and reinvestigate the space.

Finally, a primary goal of this investigation was to provide a structured method whereby the forecasting of future vehicle concept could take place. This forecasting will aid the decision maker/designer in correct allocation of research efforts and monetary expenditures.

Future work in the development of this methodology will be focused on creating an efficient means of searching a design space for feasible and viable alternatives subject to economic and technological uncertainty which yield robust solutions.

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